HIGH-RESOLUTION MONITORING AT PARKFIELD

USGS Award No.: 99HQGR0050 00HQGR0049 & 01HQGR0057

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Program Element: II; Keywords: Seismology, Earthquake Physics

Non–Technical Project Summary

This project addresses the seismic potential hazard presented by large earthquakes on the San Andreas Fault system using numerous small earthquakes combined with observations of crustal deformation of faults. It provides detailed information on the structure of active faults, on the magnitude of subsurface aseismic fault slip, on variations in deep fault slip through space and time, and on fault roughness, kinematics and physics. It also directly contributes to efforts associated with NSF's EarthScope initiative "SAFOD" and to loss reduction from earthquakes in California by providing statistics of earthquake recurrence and by delineating slip–deficit accumulation on locked faults.

FINAL TECHNICAL REPORT

USGS Award No.: 99HQGR0050

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Program Element: **II**

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Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number 99HQGR0050. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

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ABSTRACT

A high quality borehole seismometer network in place at Parkfield has fostered the evolution of a new and exciting view of the San Andreas fault–zone processes as it responds to its plate–boundary loading. The observational data and scientific inferences from this research project have been catalytic in spawning wide–ranging analyses and arguments over the fine–scale processes underway on seismogenic fault zones. Our ongoing studies at Parkfield demonstrate conclusively the existence of an extremely regular and localized process of ongoing earthquake–accommodated slip in the fault zone. Plausible assumptions lead to estimates for the spatial distribution of variations in slip–rate on the fault surface from changes in recurrence of 2000+ characteristic microearthquakes. We do not (yet) know the relationship of these variations to the M6 nucleation process but the unique findings so far have significant implications for source dynamics, for earthquake forecasting, and for scaling relations among source parameters such as fault slip, rupture dimension, stress drop and seismic moment. Compelling evidence also exists for changes with time both in seismicity and in wave propagation (from microearthquakes and from Vibroseis monitoring, and more recently from tomographic analyses of the source regions of fault–zone guided waves) that appear to be coupled, and the region of the fault zone involved is the presumed M6 nucleation volume SE from Middle Mountain. Synchronous changes well above noise levels have been seen among several parameters including seismicity rate, average focal depth, S–wave coda velocities, characteristic micro–quake recurrence intervals, fault creep and water levels in monitoring wells, and the scattering field. Recurrence–time variations in repeating sequences of small earthquakes have now been found elsewhere in the San Andreas system, including faults in the Bay Area, providing a new method for monitoring the changing strain field throughout the seismogenic zone.

Data and research results from this network provide fundamental input to models of earthquake recurrence, on spatial–temporal clustering of earthquakes, on triggering of events at distance, and on the systematic variations of slip rate on an active fault. This information is critical to earthquake risk estimation where recurrence models provide the occurrence statistics. Additionally, the real–time monitoring of fault–zone process based on these methods provides one of the rare hopes for understanding and tracking the nucleation of potential damaging earthquakes, an outcome, if eventually realized, that would be do much in reducing losses from earthquakes.

A major investment of time and money has produced a unique baseline of fault–zone behavior with distinct features observed rather than theorized, a body of observations that must be incorporated in new models for fault–zone deformation. Late in 1998 the 1980–vintage hardware finally recorded its last Parkfield microearthquake and failed irreparably. Assistance from the IRIS/PASSCAL instrument pool brought the system online in a stopgap mode. In 1999 NEHRP funds were made available to replace the system with new 24–bit data flowing seamlessly into the NCEDC data center, where the 1987–98 Parkfield data base resides. NSF funds were also provided to expand the borehole network with 3 new stations in the vicinity of the planned EarthScope/SAFOD experiment. Sustained operation of the 13 borehole station HRSN is helping to characterize seismic behavior in the target region of the SAFOD fault–zone drilling project in space and time. We have executed a basic program of operation and maintenance of the network for two years and have continued our research program using the data in the study, at very high resolution, of the spatio–temporal details of microearthquake dynamics, wave propagation and slip–rate variations. The new hardware, additional three SAFOD borehole sensors, and refinement of the triggering algorithm will soon reduce the detection threshold of the network to $M<-1.0$ in the central region.

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events at Parkfield. Recurrence–time variations in repeating sequences of small earthquakes are also providing a new method for monitoring the changing strain field throughout the seismogenic zone.

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FINAL TECHNICAL REPORT: HIGH–RESOLUTION MONITORING AT PARKFIELD

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Robert M. Nadeau (University of California at Berkeley)

Introduction

As part of the U.S. Geological Survey initiative known as the Parkfield Prediction Experiment (PPE) (Bakun and Lindh, 1985), the operation of the High Resolution Seismic Network (HRSN) at Parkfield, California, and the collection and analysis of its recordings began in 1987. **Figure 1** shows the location of the network, its relationship to the San Andreas fault, sites of significance to previous and ongoing research using the HRSN, relocated earthquake locations, and the epicenter of the 1966 M6 earthquake that motivated the PPE. The HRSN records exceptionally high–quality data, owing to its 13 closely spaced three–component borehole sensors, its very wide band–width high frequency recordings (0–125 Hz), and its sensitivity (recording events below magnitude −1.0) due to the extremely low attenuation and background noise levels at the 200–300 m sensor depths (Karageorgi et al., 1992). Several aspects of the Parkfield region make it ideal for the study of small earthquakes and their relation to tectonic processes. These include the fact that the network spans the expected nucleation region of a repeating magnitude 6 event and the transition from locked to creeping behavior on the San Andreas fault, the availability of three–dimensional P and S velocity models, a very complete seismicity catalogue, a well–defined and simple fault segment, a homogeneous mode of seismic energy release as indicated by the earthquake source mechanisms (over 90% right–lateral strike–slip), and the planned drilling zone and penetration and instrumentation site of the SAF deep observatory at depth (SAFOD) installation.

Scientific Significance. The problem addressed in this research has always been to improve our understanding of fault zone dynamics at very high resolution (meters) and to develop precise characterization methods that will allow monitoring of the subtle changes in process and properties underway within a seismogenic fault zone. Data and research results from this network are providing fundamental input to models of earthquake recurrence, on spatial–temporal clustering of earthquakes, on triggering of events at distance, on earthquake scaling and physics, on fault strength and heterogeneity, and on the systematic variations of slip rate and strain accumulation on an active fault, information critical to earthquake risk estimation and loss mitigation. Throughout its 15 years history, the Parkfield High–Resolution Seismic Net (HRSN) has acquired unique data that are forcing a new look at several conventional concepts and models for earthquake occurrence and mechanisms, and has provided a baseline and characterization of seismic activity complete down to very low magnitudes that has proven critical to many previous and ongoing studies (e.g. the SAFOD component of EarthScope).

This research began with NEHRP in 1986 as a proposed direct test with proven and modern technology of two hypotheses critical to our understanding of the physics of the earthquake process, implications for earthquake hazard reduction, and the possibilities for short–term earthquake prediction – major goals of the NEHRP:

1) That the earthquake nucleation process produces stress–driven perturbations in physical

properties of the rocks in the incipient focal region that are measurable, and

2) That the nucleation process involves progressive and systematic failure that should be observable in the ultralow–magnitude microseismicity with high–resolution locations and source mechanisms.

Little did we know then about the power of borehole networks, where remarkably low noise levels opened a window on the realm of microearthquake observations at M<0 and frequencies to 100 Hz. This unprecedented resolution has driven our research (and that of many colleagues) for the past decade, with many exciting discoveries.

In a series of journal articles and Ph. D. theses, we have presented the cumulative, often unexpected, results of this effort. They trace the evolution of a new and exciting picture of the San Andreas fault zone responding to its plate–boundary loading, and they are forcing new thinking on the physics and structure of earthquake faults in general and on dynamic processes and conditions within the fault zone at the sites of recurring small earthquakes.

Analyses of some 15 years of Parkfield monitoring data have revealed significant and unambiguous departures from stationarity both in the seismicity characteristics and in wave propagation details. Within the presumed M6 nucleation zone we have found a high Vp/Vs anomaly at depth, where the three M4.7–5.0 sequences occurred in 1992–94 and, more recently, where an anomalously high Q region in the fault zone appears through tomographic analysis to be the source volume where the fault–zone guided waves (FZGW) are generated. Synchronous changes well above noise levels have been seen among several independent parameters, including seismicity rates, average focal depth, S–wave coda velocities, characteristic sequence recurrence intervals, fault creep and water levels in monitoring wells. We have been able to localize the S–coda travel–time changes to the shallow part of the fault zone and demonstrate with numerical modeling the likely role of fluids in the phenomenon. This zone is also the upper part of the FZGW generation volume. We can connect the changes in seismicity to slip–rate variations evident in other (strain, water level) monitored phenomena.

New and unconventional scaling laws have been developed from the Parkfield earthquakes that can be projected to fit earthquakes up to M6 and to fossil earthquakes (pseudotachylite structures) of magnitudes as small as –2Mw and they predict unprecedented high stress drops and melting on the fault surface for the smallest events. The exhumed fault–zone rocks (pseudotachylite–melt) provide independent evidence for such conditions. A new asperity model for earthquakes has been developed that explains these new scaling laws. Recurrence interval variations in the characteristic event sequences (>60% of the microearthquake population) have been used to map fault slip rate at depth on the fault surface, and decomposition of the total seismicity into repeating and non–repeating seismicity has revealed a discrepancy in their b–value statistics suggesting a greater fraction of large earthquakes repeat characteristically relative to smaller quakes. Along the way in this exciting discovery process we have challenged the conventional 'constant stress drop' source model, affirmed characteristic earthquake occurrence, demonstrated the ability to detect and track temporal changes in fault–zone processes and properties. Four–dimensional maps of microearthquake processes have been produced at the unprecedented scale of a few meters. The significance of these findings lies in their apparent coupling and inter–relationships and relationships with surface deformation, from which models for fault–zone dynamics can be fabricated and tested with time.

The more general significance of the project is its production of a truly unique continuous baseline, at very high resolution, of both the microearthquake pathology and the subtle changes in fault–zone environment at depth, providing to the seismological community an earthquake laboratory available nowhere else, and the data are openly available to researchers on the NCEDC archive. This unique body of observations and analyses has also provided much of the impetus for Parkfield as the preferred site for deep drilling into an active seismogenic fault zone (SAFOD), and the network has just completed a total hardware upgrade to modern real–time telemetry and data flow into the BDSN stream. With NSF support, we have added three new borehole stations to better focus on the SAFOD drilling target, bringing the detection threshold there to less than −1.0Mw so that a complete baseline of seismicity will be available when drilling begins. The evolution of our research effort can best be summarized in the following list of our major publications.

Reducing losses from Earthquakes in the U.S. A better understanding of earthquake physics, processes and recurrence models are critical to reducing losses from earthquakes in the U.S., and this research is arguably fundamental to these goals. Results obtained from this data collection and research effort provide unique information on the strain accumulation on faults at depth, estimation of the strength and strength heterogeneity of earthquake generating faults (i.e. fault roughness), and on scaling properties of earthquake recurrence times and rupture parameters, all of which are critical input for accurate earthquake forecasts, fault rupture models, and ground motion and earthquake hazard estimation. Uniquely, through the study of characteristically repeating small earthquakes this work can also provide direct tests of earthquake forecast models by making predictions based on these models and assessing their success rates on time scales of months to a few years as opposed to decades to centuries as required for similar tests using large magnitude events.

Recent Findings

Based on the ubiquitous clusters of repeating microearthquakes at Parkfield, scaling laws have been developed that can be projected to fit earthquakes up to M6, and they predict unprecedented high stress drops and melting on the fault surface for the smallest events. Exhumed fault–zone rocks provide independent evidence for such source conditions (Nadeau et al., 2002).

This hypothesis is being debated vigorously in the current literature. Recurrence interval variations in the characteristic event sequences (about one–third of the microearthquake population) have been used to map fault slip rate at depth on the fault surface, and this technique appears to be applicable to other types of faults (Nadeau and McEvilly, 1999; Burgmann et al., 2000). Along the way in this exciting discovery process we have challenged the conventional 'constant stress drop' source model, affirmed characteristic earthquake occurrence and developed four– dimensional maps of fault–zone microearthquake processes at the unprecedented scale of a few meters (Nadeau and Johnson, 1998; Nadeau and McEvilly, 1999). The significance of these findings lies in their apparent coupling and inter–relationships, from which models for fault–zone process can be fabricated and tested with time. A more fundamental contribution of the project is its production of a continuous baseline, at very high resolution, of both the microearthquake pathology and the subtle changes in wave propagation, providing to the seismological community a dynamic earthquake laboratory available nowhere else. This unique body of observations and analyses has also provided much of the impetus for Parkfield as the preferred site for deep drilling into an active seismogenic fault zone (the SAFOD project), and we have upgraded and expanded the network to improve its view of the drilling target zone on the fault surface (**Figure 1**).

The data and previously derived theoretical and empirical relationships from Parkfield have served as a basis for investigations on a variety of topics by BSL researchers and collaborators at the Department of Terrestrial Magnetism (Carnegie) and Lawrence Berkeley National Laboratory (LBNL).

Johnson and Nadeau (2002) developed an empirically based earthquake asperity model that explains previously determined earthquake scaling relationships from characteristically repeating earthquake sequences (CS) at Parkfield. Their model suggests fault strength to be highly heterogeneous.

Korneev et al. (2002) have used Fault Zone Guided Waves (FZGW) from HRSN recorded microearthquakes to image the structure of the innermost fault zone using FZGW attenuation. They showed that the boundary between locked and creeping fault at depth could be delineated using FZGW data from microearthquakes recorded at only 2 of the HRSN borehole stations located in the fault zone (**Figure 2**).

Niu et al. (2002) have used Parkfield CS events as highly repeating illumination sources to reveal the stress–induced migration of scatterers of seismic energy. By examining the systematics of temporal changes in the coda arrivals of CS events and stress changes inferred from the evolution of deformation at Parkfield, they infer that stress–induced redistribution of fluids along fractures in or adjacent to the fault are taking place.

Using the scaling (Tr–Mo) of CS recurrence intervals (Tr) with seismic moments (Mo) (Nadeau and Johnson, 1998) and the its calibration with intermediate scale geodetic measurements at Parkfield, Schmidt et al. (2002) and Nadeau and McEvilly (2002) are mapping areas of deep fault slip and slip rates along the East Bay Area Hayward Fault and along the central creeping section of the San Andreas Fault (SAF) in California.

In ongoing investigations of the Tr–Mo scaling, BSL researchers have extended the range in Mo over which scaling occurs to over 15 orders of magnitude in Mo (**Figure 3**). This relationship serves as a basis for empirical determinations of earthquake source parameters of area (A), seismic slip (d), and stress drop (Nadeau and Johnson, 1998). These determinations involve relatively few model assumptions and are independent of existing models relating the shape and spectra of seismic waveforms to the mechanics of earthquake sources. Results of the CS based approach predict results that are significantly different from the standard models derived from the waveform base methods.

Another principal focus of BSL's recent research at Parkfield has been the detailed analysis and monitoring of the characteristics of microseismicity with in the drilling and penetration zone of the SAFOD component of the NSF initiative EarthScope. Of particular interest is the evolution of fault zone deformation and detailed seismic structure immediately surrounding the repeating SAFOD M2 target zone, and the recurrence behavior and size of the two potential M2 targets (separated by 70m).

Using a 3–dimensional double–difference code developed by Alberto Michelini in Italy and a preexisting 3–D cubic splines interpolated velocity model developed from HRSN data (Michelini and McEvilly, 1991), we have been able to resolve the relative seismic structure in the target zone in great detail (Nadeau et al., 2001) (**Figure 4**). The relocations indicate that the subhorizontally drilled portion of the SAFOD hole may need to penetrate a seismically active (and the existence of CS imply actively slipping) strand some 300m to the SW before entering the M2 target region.

CS exist on both strands and slip rates on the strands inferred from the Tr of the CS in the strands indicate that both are slipping at about 10 to 15 mm/yr. This suggests a distinct possibility of shearing of the deep borehole casing on the SW strand which needs to be taken into account if long term monitoring of the local target is to take place.

The Tr–Mo relationship and ongoing monitoring of the Tr's of the CS local to the M2 target(s) can also be used to help estimate the expected occurrence time of the next M2 repeat. This information will be helpful in the planning of SAF penetration and monitoring efforts, as well as for testing of earthquake recurrence forecast models, and for evaluating the conditions surrounding the M2 target(s) leading up to failure.

The SAFOD experiment will also measure deformation along the deep hole which will provide a direct calibration of slip rates at depth with CS Tr's near the target zone. This will provide ground truth for interpretation of the Tr–Mo relationship, and is crucial for establishing an accurate model of CS recurrence behavior, for interpreting Tr–Mo based source parameter scaling relationships, for the extrapolation of fault and earthquake physics based on the Tr–Mo scaling, and for application of the CS deep fault slip rate method to slipping faults generally.

In regards to the drilling operation, the calibration will also provide a better picture of the M2 target size by providing a more accurate estimate of the partitioning of Mo from the expected M2 event (Mo=GdA) into its seismic slip (d) and rupture area (A) dimensions. Currently, estimates of the dimensions of the M2 target(s) vary significantly depending on the expected stress drop of the M2 events on the patch.

More information about the role of HRSN research in the SAFOD project is available from the Berkeley Seismological Laboratory Annual Report 2001–2002, available on the Web at:

http://www.seismo.berkeley.edu/seismo/annual_report/ar01–02

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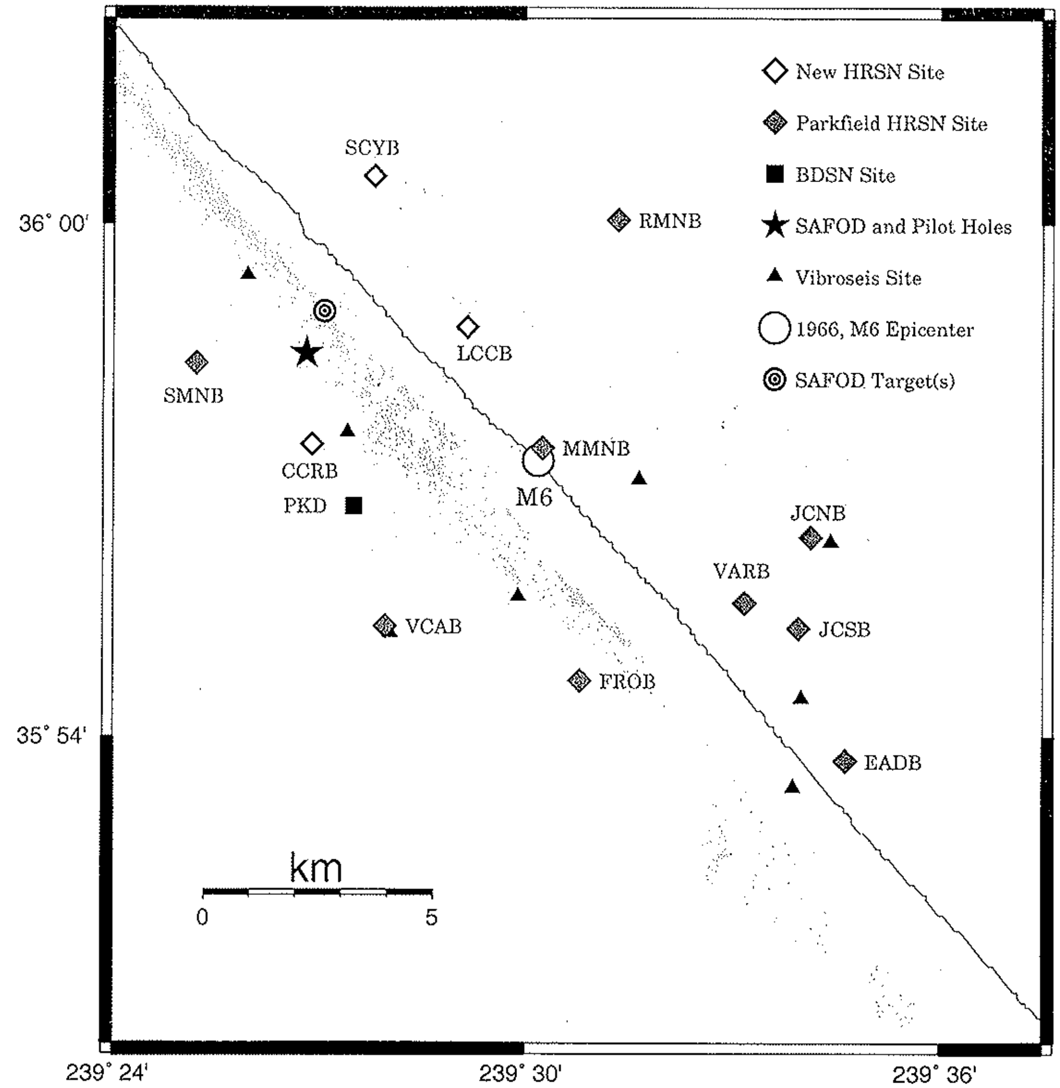

Figure 1. Map showing the San Andreas Fault trace, the location of the original 10 Parkfield HRSN stations (filled diamonds) and the 3 new sites (open diamonds), along with the BDSN station PKD (filled square). The locations of the 8 source points for the Vibroseis wave propagation monitoring experiment are represented by small black triangles. The epicenter of the 1966 M6 Parkfield main shock is located at the large open circle. ,The location of the pilot hole and proposed SAFOD drill site is shown by the filled star, and the location of the 2 alternative M2 repeating earthquake targets (70 meters apart) are shown as concentric circles. Seismicity relocated using an advanced 3-D double-differencing algorithm applied to a cubic splines interpolated 3-D velocity model (Michelini and McEvilly, 1991) is also shown (grey points). Station GHI (Gold Hill, not shown) is located on the San Andreas Fault about 8 km to the Southeast of station EAD.

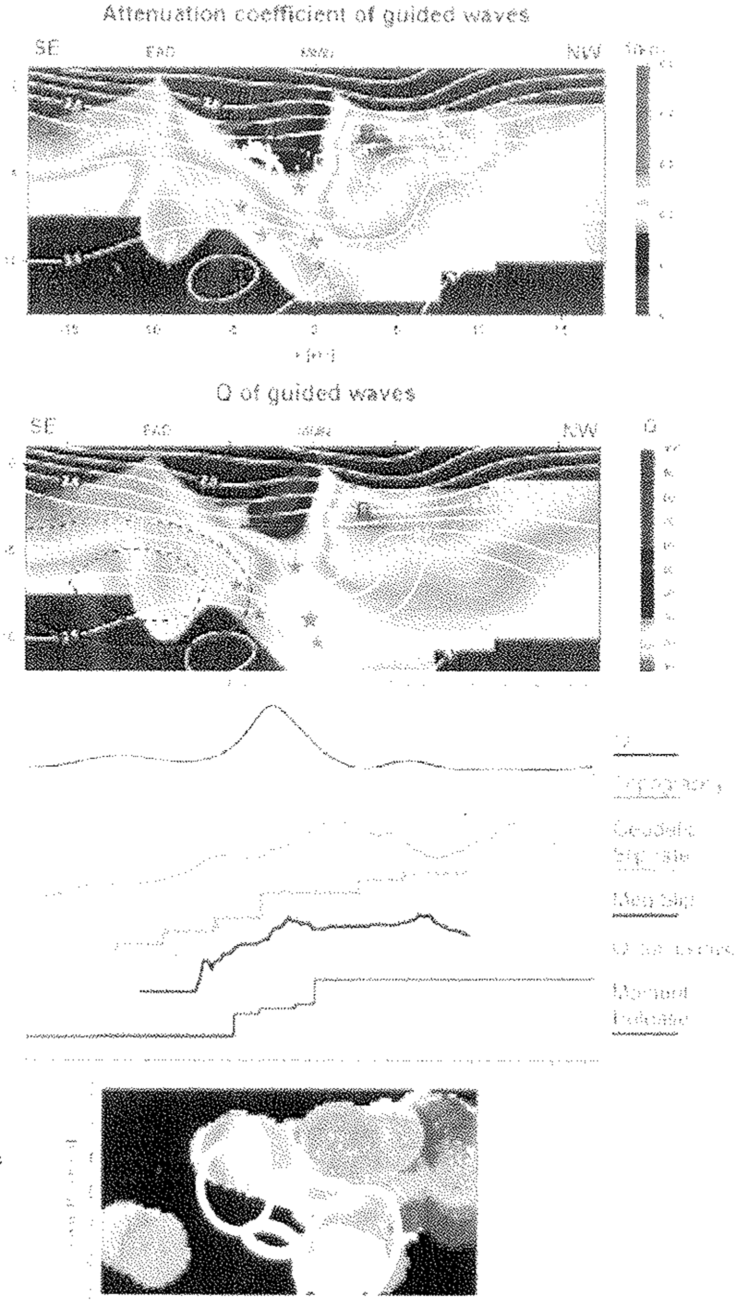

Figure 2. Spatial relationship of the FZGW attenuation/Q anomaly with other observations along the Parkfield segment of the San Andreas fault zone. Top 2 panels show in-fault attenuation and Q images resulting from the FZGW tomographic reconstructions. Not the NW-plunging zone of low FZGW attenuation (high Q) in the central portion of the panels delineating the transition at depth of locked to creeping fault. Also shown are Vs contours, 1987-1998 seismicity (white dots and small red stars for the 4 recent M>4 events), and the 1966 M6 hypocenter (large red star). The center panel shows the function of FZGW Q taken along a profile at 3 km depth. Shown immediately below the Q curve are curves representing topography along the fault (green), surface fault slip rates from geodetic data (Harris and Segall, 1987, in grey), slip rates in the depth range 0 to 5 km inferred from recurrence intervals of characteristic microearthquake sequences (black), the cumulative Q function taken along the fault segment (SE to NW, pink) and the 1987-1998 moment release as a cumulative function along the fault from SE to NW (blue). The bottom panel shows the along fault deep slip rate distribution at Parkfield inferred from the recurrence times of characteristic microearthquakes occurring between mid-1992 and 1995 (inclusive, see Nadeau and McEvilly, 1999), and the aftershock regions of the M>4 earthquakes occurring during this time period. Along fault features in all these characteristics correlate spatially and appear to delineate the transition from locked to creeping behavior on the surface and at depth on the SAF at Parkfield.

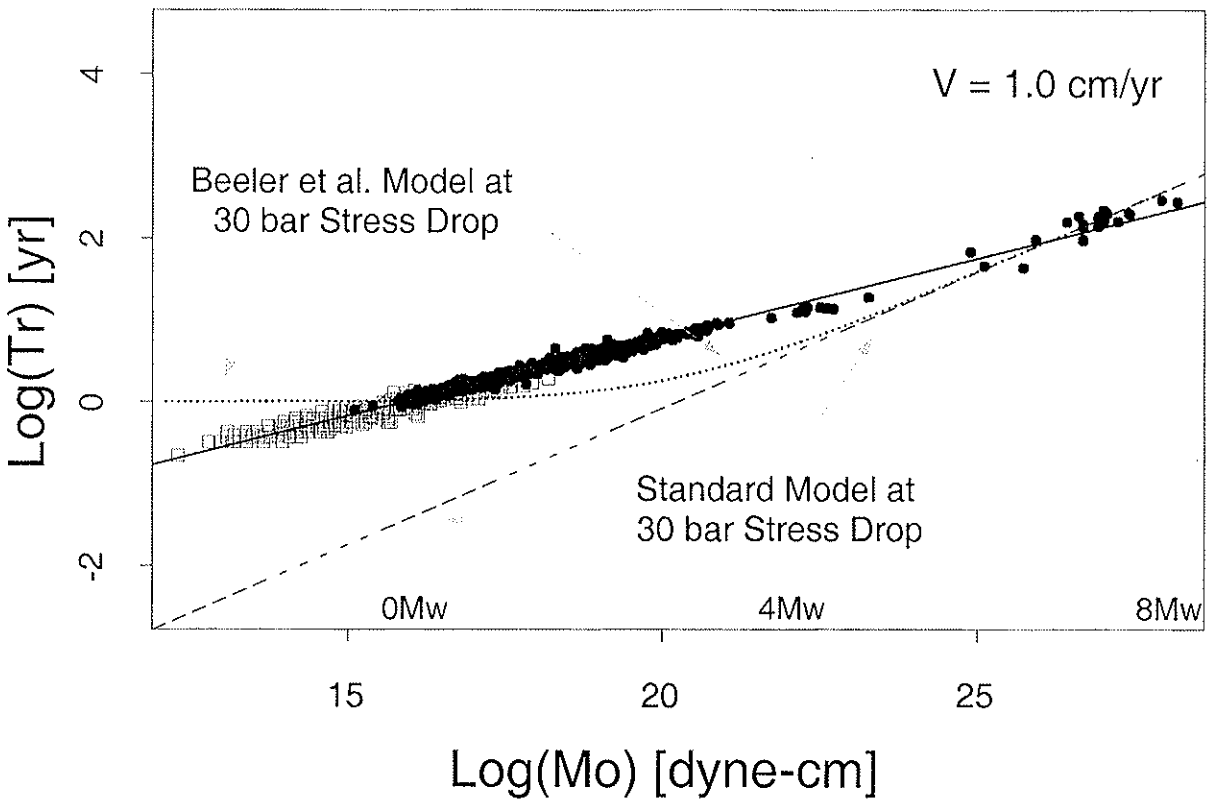

Figure 3. Log characteristic sequence recurrence time verses seismic moment normalized to a fault loading rate of 1 cm/yr. Filled circles show data for modern and historical characteristic events in California. Open squares are infer red Tr and Mo of fossil earthquakes (pseudotachylites) found near Palm Desert California (Wenk et al., 2000). Black line is a least squares fit to the characteristic earthquake data. Also shown are the predicted Tr-Mo curves for the standard constant stress drop Model (calculated for 30 bars, dashed straight line) and the creep-slip model of Beeler et al. (2001) (dotted line).

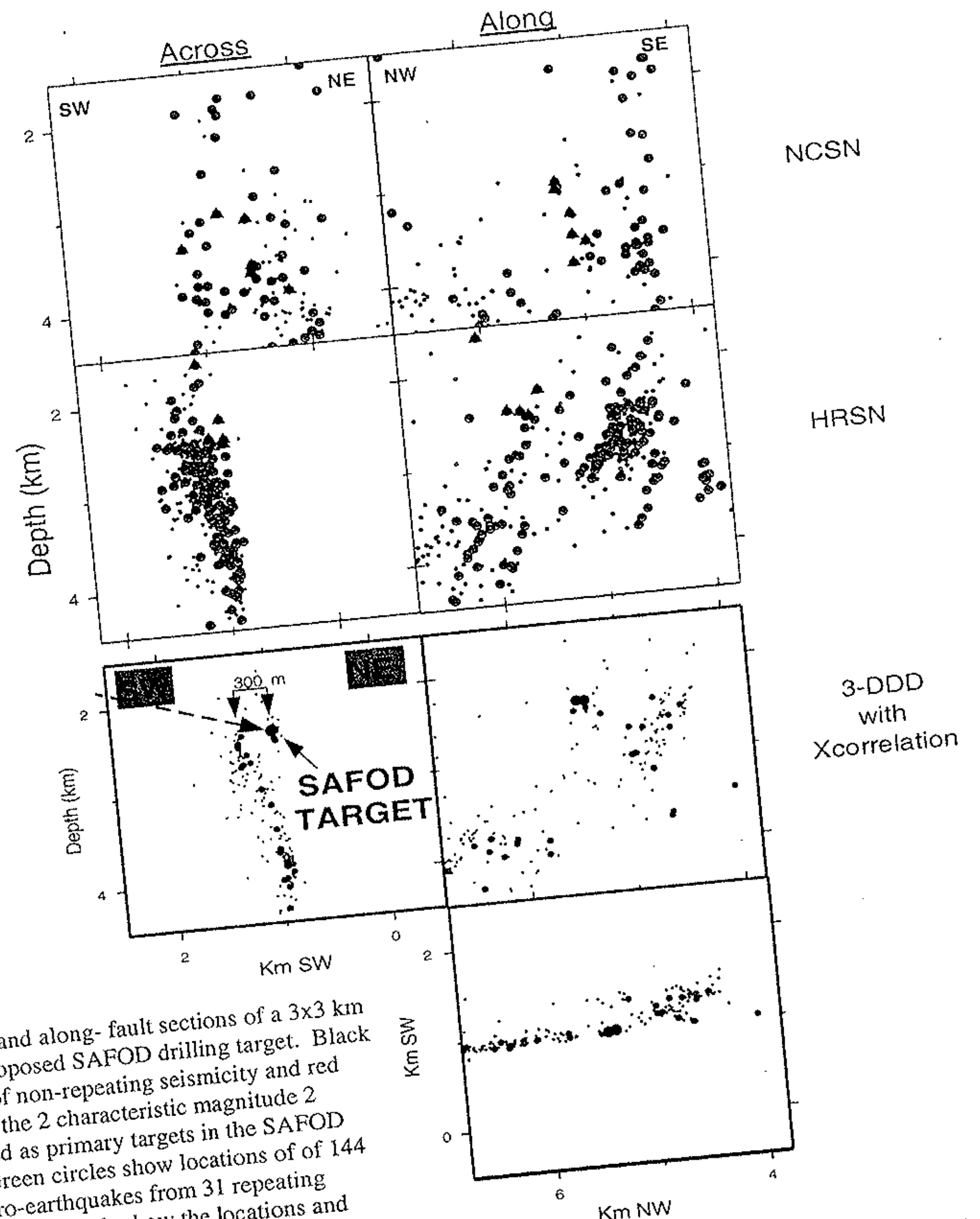

Figure. 4 Across- and along- fault sections of a 3x3 km region about the proposed SAFOD drilling target. Black dots are locations of non-repeating seismicity and red triangles represent the 2 characteristic magnitude 2 sequences proposed as primary targets in the SAFOD drilling project. Green circles show locations of of 144 characteristic micro-earthquakes from 31 repeating sequences. Upper two panels show the locations and available events from the routine NCSN catalog that has relative location uncertainties of about +/- 1000m. In the two panels directly below, HRSN locations with relative location accuracies of about 150-200m are shown. The lower panels show the same events relocated using our 3-DDD algorithm and cross-correlation using identical phase picks and weights for event pairs. At lower resolution (upper) the characteristic earthquakes scattered widely. As resolution increases (bottom 3 panels including map view of the target region), their locations collapse onto 31 distinct sites of repeating earthquake activity from which fault slip rates can be determined at depth. Also seen at the highest resolution, are two distinct parrallel strands of the SAF separated by about 300 m. The NE strand contains the proposed SAFOD drilling target(s) and both strands are slipping at about 10 to 15 mm/yr as indicated by the repeating earthquake activity located on both. The drill hole is planned to penetrate the M2 targets subhorizontally from the southwest (SW) (approximately perpendicular to the SAF). With this proposed geometry, the actively slipping SW strand must first be penetrated (and the borehole remain intact) in order to proceed to the target. Whether the borehole will remain intact for the coring phase of the experiment and longer term monitoring remains an open question.